STUDY OF FREQUENCY TRANSFER VIA OPTICAL FIBER IN THE MICROWAVE DOMAIN

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Abstract

Technical issues are investigated for a precise frequency transfer system using two-way signals by wavelength division multiplexing (WDM) in a single fiber. Bi-directional optical amplifiers are necessary to make the distance longer. Frequency stability is shown in the tandem optical amplifier link where the amplified spontaneous emission (ASE) noises are accumulated. Increasing transmission speed is effective for improving the system performance; however, chromatic dispersion of the fiber degrades the frequency stability significantly in an experiment with 10 GHz signal and 50-km fiber. The degradation can be improved by using 1550 nm zero-dispersion-shifted fiber (DSF) instead of SMF. Effects of polarization mode dispersion (PMD) and polarization scrambling are experimentally shown with a differential group delay (DGD) generator. It is also important to use stable oscillators for stability evaluation, since the time difference between the original and the received signal at the far end degrades the performance if the phase noise of the OSC source is not small enough.

INTRODUCTION

Time and frequency standards are widely used in a broad area of applications in industry, science, navigation, and telecommunications. In accordance with the progress of next generation frequency standards, excellent performances of frequency transfer systems using optical fiber have been demonstrated by many groups (for example, **[1-8]**). For instance, it is reported that the frequency stability of 10^{-15} at 1 s and 10^{-18} at a 1-day averaging time for optical link in the microwave domain **[6]**. This paper describes our transfer system configurations with a newly developed bi-directional amplifier and technical items to be solved for the systems. The experimental results are shown in terms of several factors, such as input optical power to photo-detectors, transmission frequencies, fiber types, stability of the source oscillator (OSC) for improving frequency stability, and precise evaluation.

Report Documentation Page

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1. REPORT DATE **NOV 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Study of Frequency Transfer via Optical Fiber in the Microwave Domain**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Metrology Institute of Japan (NMIJ),Ibaraki, 305-8563, Japan,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
41st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 16-19 Nov 2009, Santa Ana Pueblo, NM

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

SYSTEM CONFIGURATIONS

The systems for both frequency comparison and distribution use bi-directionally transmitting dense-wavelength-division-multiplexed (D-WDM) signals along a single fiber. A continuous wave (CW) light source in 1550 nm region is directly or externally modulated with microwave reference signals. The wavelength separation of the two signals is 0.8 nm (i.e. 100 GHz), which is compatible with values in the recommendation by the International Telecommunication Union and is widely used in recent telecommunication networks. The light signal is directly detected by a photodiode.

The comparison system should be capable of long-distance transfer between two frequency standards. The distance will be several hundred kilometers for regional applications and 10,000 km in the ultimate sense for international applications. Round trip time becomes 0.1 s in that case and this makes it difficult to realize a precise phase compensation system. In our system, phase comparisons of the received signals and the frequency standards at each terminal are used for frequency transfer without the phase compensation (offline data processing). As for frequency distribution system, real-time use is a must, since the signal is used as a timing signal for particle accelerators or radio astronomy applications. The distance is 50 km at most in those applications.

TECHNICAL ISSUES FOR THE SYSTEM

There are technical items to be solved for the precise transfer systems. We show investigated results about bi-directional amplifiers to compensate the fiber loss for long-distance transfer, accumulated noise effects from the tandem optical amplifiers, system performance improvement by high-speed signal, degradation caused by fiber chromatic dispersion, and polarization mode dispersion.

BI-DIRECTIONAL OPTICAL AMPLIFIER AND THE NOISE EFFECT

The developed optical amplifier has an optical isolator in each two-way channel divided by wavelength filters to suppress the optical reflection that causes amplification instability. The additional insertion optical loss due to this method is about 1.5 dB. The optical gain greater than 30 dB is obtained for both signals, with a good optical isolation of 65 dB. The loss of the long-distance fiber can be compensated by the tandem amplifiers; however, amplified spontaneous emission (ASE) noise, as shown in Fig. 1, from each erbium-doped fiber amplifier (EDFA) degrades the received signal-to-noise ratio. The Allan deviation at averaging time (τ) of 1 s is shown in Fig. 2 (dashed lines) for K = 1, 10, and 100 at 10 MHz and 10 GHz, respectively (K is the total number of amplifiers). The optical amplifier gain is 20 dB, with a noise figure of 6 dB in this calculation. The optical filter bandwidth, Δf, is set to 100 GHz so as to make 10-GHz signal transmission possible. The Allan deviation improves as the input power is increased, as shown in Fig. 2; however, the slope approaches -1/2 in the log-log plot in the high input power region (e.g., over about 0 dBm for K = 1), because the Signal-ASE beat noise becomes dominant. It is the interference (beat) noise between the signal light component and the ASE noise. As K is increased, the Allan deviation degrades, as shown in Fig. 2. The figure shows the Allan deviation on the order of 10^{-15} at τ = 1 s is possible for 10 GHz and K = 100 when the optical averaged input power is over -20 dBm or so. A hundred optical amplifiers (K = 100) can make a 10,000 km transfer with an amplifier spacing of 100 km.

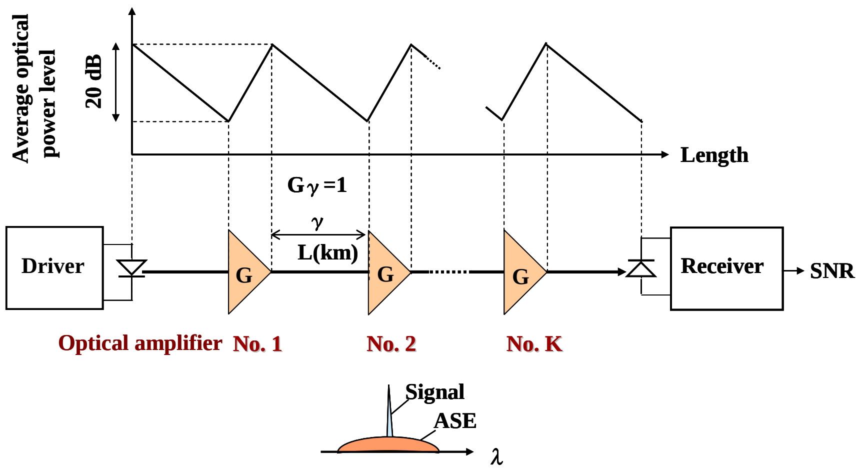


Fig. 1. Optical amplified system and signal level diagram.

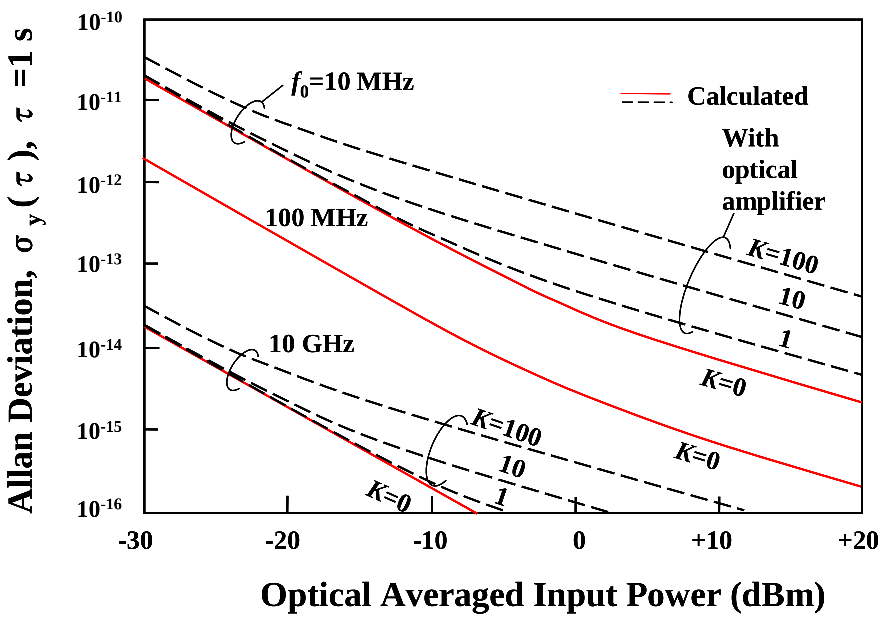


Fig. 2. Frequency stability at an averaging time of 1 s in the tandem optical amplifier system.

SHORT-TERM STABILITY IMPROVEMENT BY HIGH-SPEED SIGNAL

As already pointed in **[1]**, increasing the modulation signal frequency f_0 as well as increasing SNR is effective to improve the short-term stability. Figure 3 shows the calculated stability taking account of the signal shot noise and the thermal noise of the receiver. The ASE noise is not considered here. The experimental results were obtained in a setup by an optical transmitter to a detector with a variable attenuator instead of a long fiber (the fiber effect is not considered). If f_0 is 100 MHz, the Allan deviation on the order of 10^{-14} at τ = 1 s is possible if the input power is around -10 dBm, as shown in Fig. 3. It becomes 2×10^{-15} (+5 dBm input power) for a 1-GHz signal. The value was improved to 8×10^{-16} (+3 dBm) by using a 10-GHz signal. The measured values were worse than the calculated values in the high-frequency region. The possible reasons for this are measurement system noise limit (4×10^{-16} for 1 GHz, 1×10^{-16} for 10 GHz at τ = 1 s), not enough modulation depth, photodiode excess noise in the high-power region **[9]**, and coupling efficiency difference of the photo- detector modules for 100 MHz, 1 GHz, and 10 GHz.

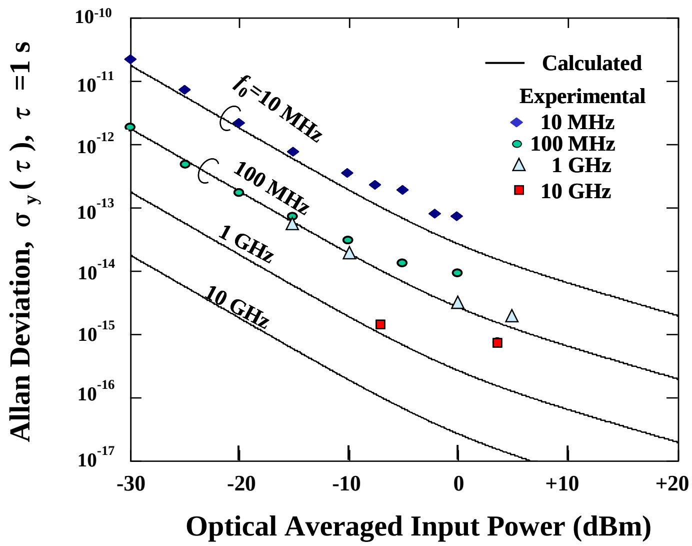


Fig. 3. Short-term frequency stability for high-speed signals.

FIBER CHROMATIC DISPERSION AND THE DSF EFFECT

Although the stability can be improved by modulation with a high-frequency signal, as stated above, chromatic dispersion effects must be considered. The group delay difference between the optical carrier and the modulated side band signals degrades the stability if the frequency fluctuation of laser diode is not small enough. This effect was reported by European groups with a 1-GHz signal ("dispersion noise" in **[6]**). The dispersion noise is considered to be significant for signals at high frequencies. We measure the effect with a 10-GHz signal, as shown in Fig. 4. A cryogenic sapphire oscillator (CSO) was used as the microwave signal source. The frequency of the CSO is 10.81 GHz **[10]**. The wavelengths for λ_1 and λ_2 are 1550.92 and 1551.72 nm, respectively. Both received two-way 10.81-GHz signals were converted to 10 MHz by a common local oscillator (10.80 GHz) using the dual-mixer time difference (DMTD) method, and the phase difference between the 10-MHz signals was measured by commercial equipment. This combination method was confirmed in **[11]**. The total DMTD measurement system noise level was 1×10^{-16} at τ = 1 s, as shown in Fig. 5. The optical system (the transmitter to the receiver) noise floor is also shown in Fig. 5 using a short fiber (2 m). The short-term stability was 2.2×10^{-15} at τ = 1 s when the input optical power to each photodiode (PD) was +3.0 dBm to PD 1 and +3.5 dBm to PD 2. It was degraded to 1×10^{-13} at 1 s when using a 50-km single-mode fiber (SMF). Because of the fiber loss, the input power values decreased to -5.4 dBm (PD 1) and -4.9 dBm (PD 2). The main reason of this degradation is dispersion noise, since the SMF has a typical dispersion of 17 ps/km/nm **[12]**. The group delay difference becomes 68 ps. In this case, selection of dispersion-shifted fiber (DSF) **[13]** is effective, since the dispersion is minimized in the 1550 nm region where the attenuation is also minimized. The value was improved to 2.3×10^{-14} at 1 s by using 50-km DSF. The loss of DSF is little bit larger (about 0.02 dB/km) than the loss of SMF. So the input power level became -6.5 dBm (PD 1) and -5.9 dBm (PD 2). The improvement by DSF is significant, however; the value is degraded by one digit compared to the optical system noise floor level. When we applied polarization scrambling for both transmitting signals, instabilities of 8×10^{-15} at 1 s and 1.2×10^{-18} at a 1-day averaging were obtained, though the input optical power values decreased to -7.7 dBm (PD 1) and -7.0 dBm (PD 2) because of additional insertion loss of the scrambler. The scrambling effect is investigated in the next section.

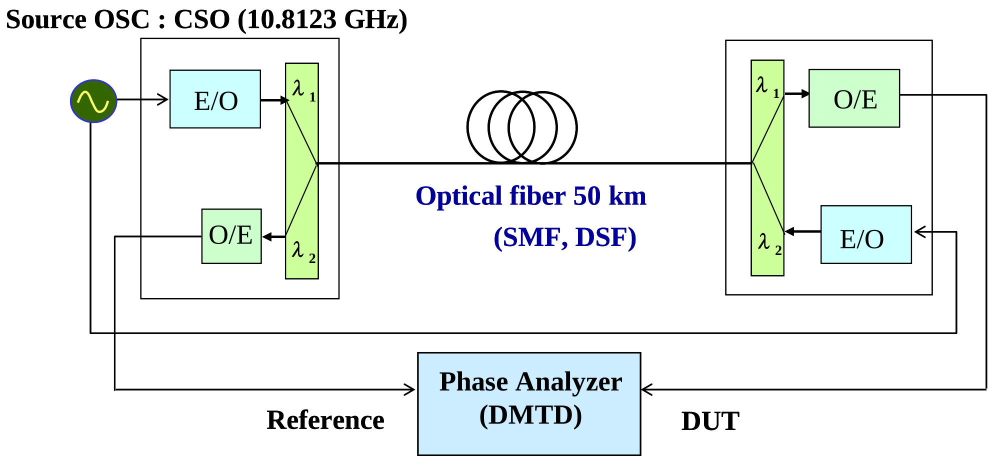


Fig. 4. Experimental setup for measuring fiber effects (E/O; electrical-to-optical converter, O/E; optical-to-electrical converter).

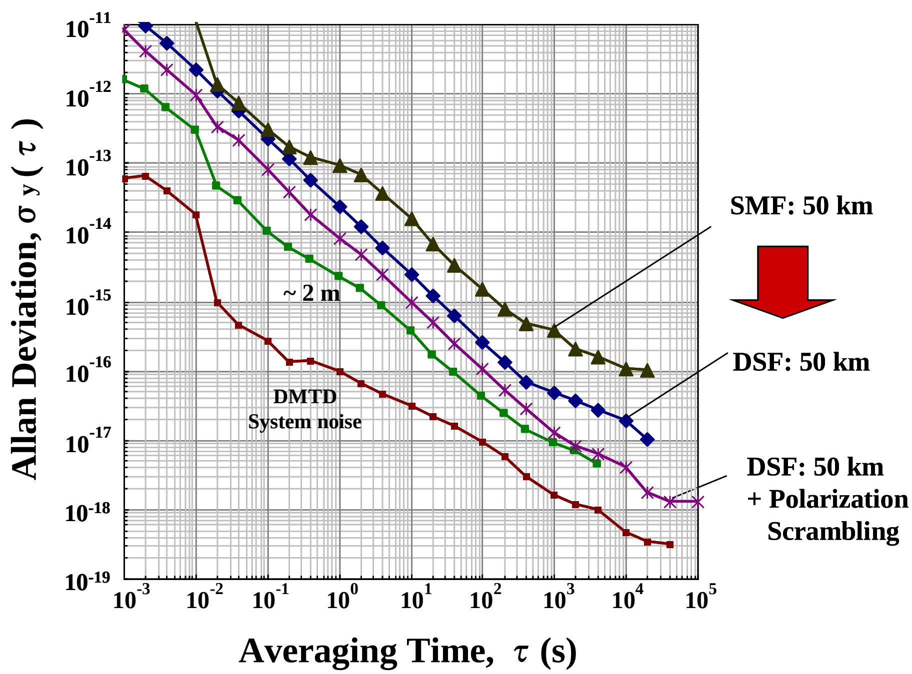
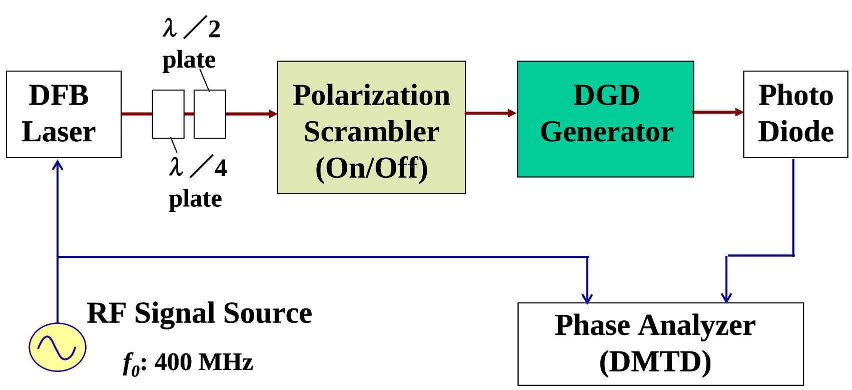


Fig. 5. Experimental results for two fiber types (SMF and DSF).

POLARIZATION MODE DISPERSION AND SCRAMBLING EFFECT

The transmission signals are distorted by the differential group delay (DGD) between the two principal states of polarization in a fiber. The time-averaged DGD is defined as the polarization mode dispersion (PMD). The PMD effects were stated in **[14]**; for instance, PMD-induced degradation is significant and so the scrambling is effective for microwave transfer **[6]**. In other measurement for optical carrier transfer **[15]**, there is no such effect, mainly because of the small PMD coefficient (0.02 ps/km$^{1/2}$), which is relatively small compared to the maximum value of 0.5 ps/km$^{1/2}$ in the recommendation **[12]**. We have checked the effects by using a commercial DGD generator that is widely used for evaluating telecommunication system performance. A polarization scrambler is also serially located, as shown in Fig. 6. Therefore, we can verify the sole effect of PMD or scrambling without optical input power change or fiber chromatic dispersion effect, etc. A λ/4 plate and a λ/2 plate are used for adjusting incident polarization so as to make the DGD maximum. Figure 7 shows the experimental result with setting an average PMD value of 7 ps for the Maxwellian distribution (the number of DGD samples were 10^4 with the 1 ms duration of each DGD value before changing to another). The time difference was obtained every 1 s from a commercial time-interval analyzer (400 MHz available), as plotted in Fig. 7. The phase fluctuation of 400 MHz signal was reduced to 1/10 or less by the scrambler with a scrambling frequency of 700 kHz. This frequency is fast enough for averaging out PMD effects compared to the 1-ms duration of the DGD state. Figure 8 shows the frequency instability. Optical input power to the photodiode was +6.5 dBm for all conditions with a 400-MHz signal. The Allan deviation decreased in inverse proportion to the averaging time. The Allan deviation at 1 s was 5.6×10^{-13} for a PMD of 1ps. This corresponds to 100 km if the PMD coefficient of a fiber is 0.1 ps/ km$^{1/2}$. By scrambling the polarization, it was improved to 6.4×10^{-14}, almost close to the system noise floor. The stability was degraded to 3.7×10^{-12} by a PMD of 9 ps, corresponding to 8,100 km (if 0.1 ps/ km$^{1/2}$ is assumed); however, it was improved by an order of magnitude by the scrambler, as shown in Fig. 8.



Fig, 6. Experimental setup for measuring the effects of PMD and scrambling.

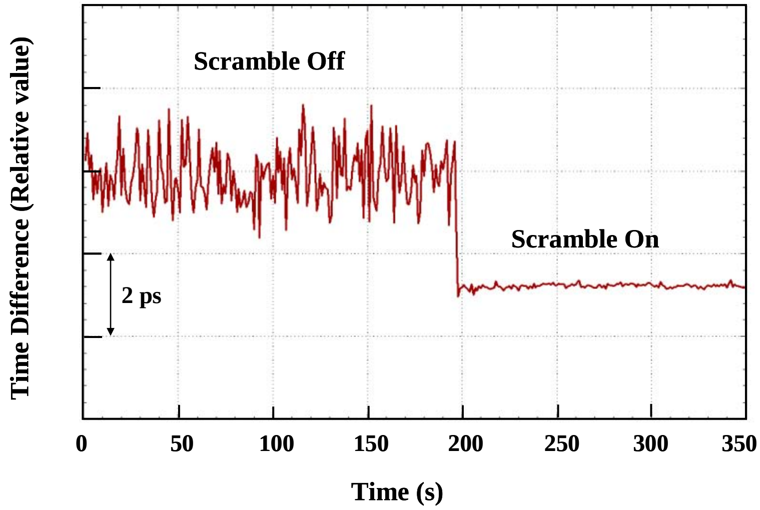


Fig. 7. Polarization scramble effect for a PMD of 7 ps.

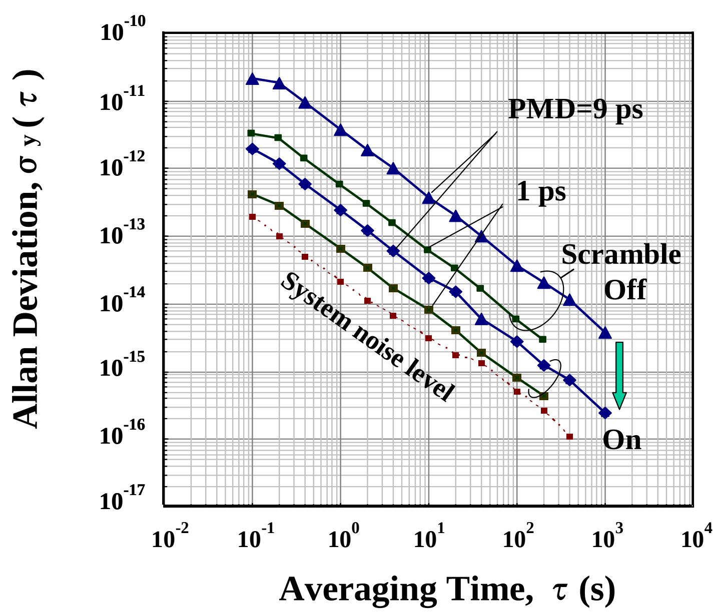


Fig. 8. The frequency instability for the PMD values of 1 ps and 9 ps, and scrambling effects.

Effect of OSC Source Instability in Fiber System Evaluation

There is concern about effects of OSC source instability for evaluation of long fiber systems, since the time difference between the original signal and the received one at the far end degrades the performance if the phase noise of the OSC source is not small enough. We measured the effects in the experimental setup, as shown in Fig. 9. We used a crystal OSC (XO), a hydrogen maser (H-maser), and a cryogenic sapphire oscillator (CSO) as a reference signal source. Figure 10 shows test results for 100-MHz signals of the H-maser and the XO with an external long-term stable reference. The input optical power to the optical receiver was adjusted to -0.4 dBm by a variable optical attenuator for each fiber length, 2 m, 25 km (the corresponding time delay is about 125 μs), and 50 km (about 250 μs). Although there was degradation by the fiber insertion, this settled in the range of the stability of the H-maser, as shown in Fig. 10 (a). The stability degradation at around 100 s for 25 km and 50 km fibers is caused by room temperature change. On the other hand, this was significantly deteriorated to the instability level of the XO when using the XO, as shown in Fig. 10 (b).

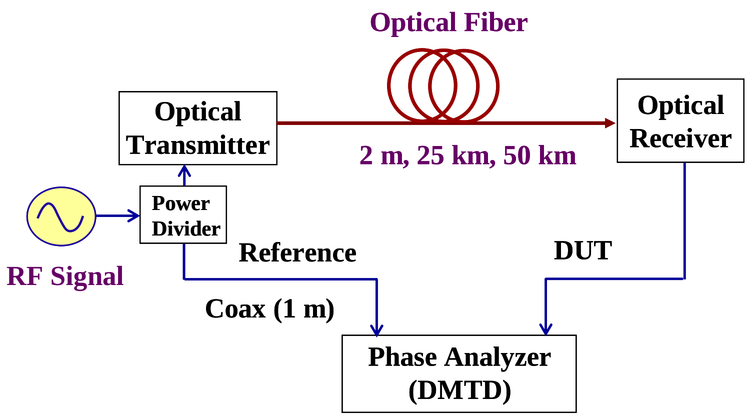


Fig. 9. Experimental setup for measuring effects of OSC source instability.

Figure 11 shows experimental results for the free-running XO (f_0 = 400 MHz) with its frequency instability. This case also shows deterioration in two digits for one-way transmissions (25 km and 50 km), as shown in Fig. 11 (a). The amount of deterioration depends on the short-term stability of the reference signal. The group delay difference between two signals by WDM are quite small; therefore, there is no significant deterioration in an experimental setup like Fig. 4, as shown in Fig. 11 (b) for both the counter and same directions in each other by two-way WDM transmission (no phase compensation). Figure 12 shows the results for the CSO, which has an ultra-high short-term frequency stability of 1.1×10^{-15} at τ = 1 s **[10]**. In this experiment, the DSF fiber of 50 km and polarization scrambler were used to reduce the dispersion noise and the PMD effects described above. There is a difference of almost two digits between the two Allan deviations at $\tau = 10^{-3}$ s for the CSO and a 10.81-GHz signal from a signal generator being phase-locked to the H-maser. When using the signal generator, the Allan deviation was 1.3×10^{-13} at τ = 1 s, which is almost equal to the level of the H-maser. Because of the experimental room temperature change, the fiber-induced instability of about 1×10^{-14} was observed for the averaging time over around 1 s. This fluctuation level is the same as the level in Fig. 10 (a). The value estimated from the trend of the short-term stability from 1 ms to 40 ms is on the same order as the value in Fig. 5 (8×10^{-15} at 1 s). These results show that CSO-level short-term stability is required for evaluating system performance on the order of 10^{-15} at 1 s even if the fiber length is 50 km. In phase compensation systems, the transmitting signals, that are phase-controlled with the reference signals, propagate in fiber cables. Therefore, the reference signal source stability is one of items to be considered for precise evaluation.

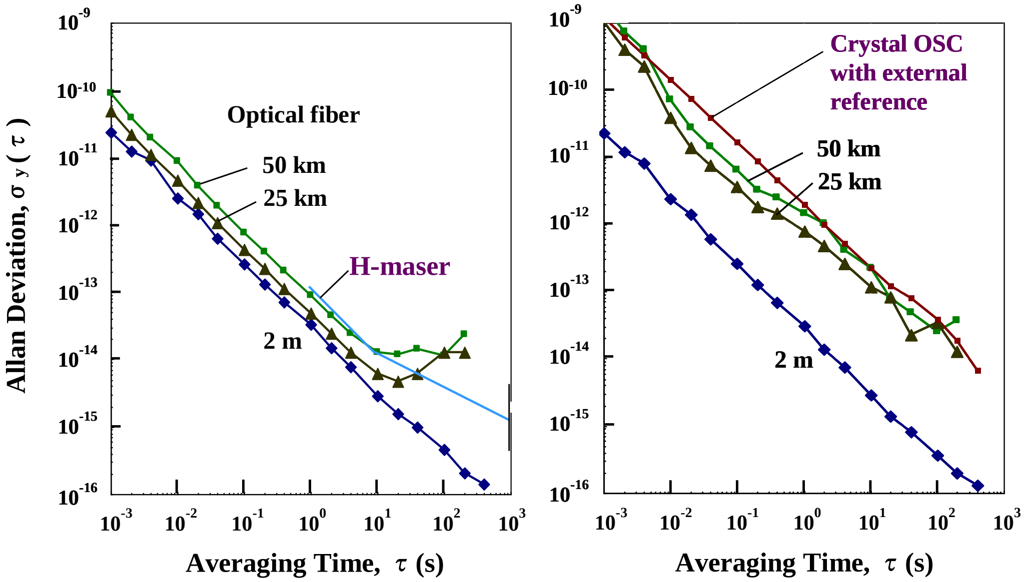


Fig. 10. Frequency instability in the measurements for the H-maser (a) and the crystal OSC with a stable external reference signal (b).

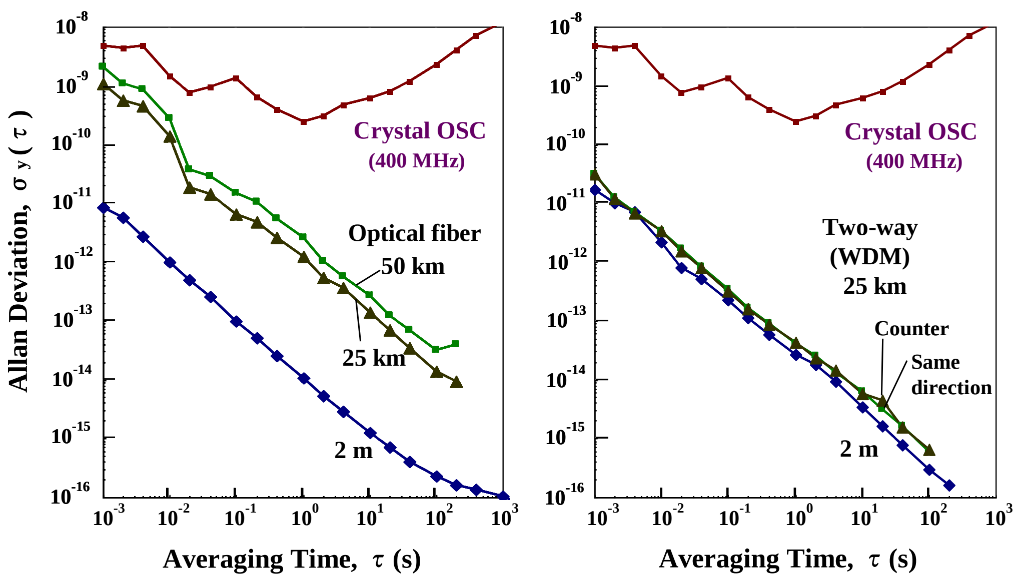


Fig. 11. Frequency instability for the free-running XO. (a) One-way transmission; (b) two-way transmission by WDM.

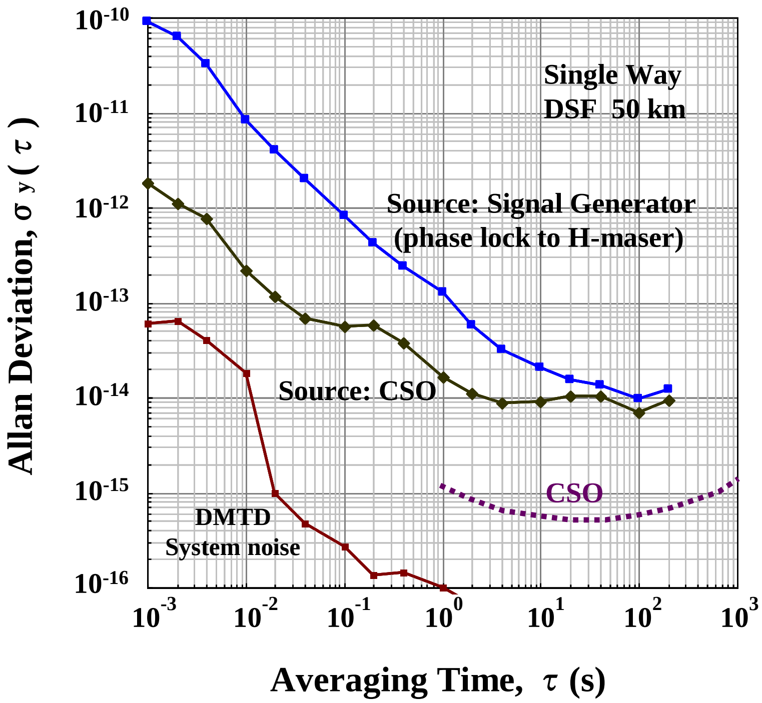


Fig. 12. The frequency instability with the CSO as the reference signal source.

SUMMARY

Technical issues were investigated for a precise frequency transfer system using two-way signals by D-WDM. The frequency instability induced by the ASE noise was calculated in the tandem bi-directional optical amplifiers. The results indicated the possibility of an international transfer with the Allan deviation on the order of 10^{-15} at $\tau = 1$ s by high-speed (10-G Hz) signal transmission. However, chromatic dispersion of the fiber degraded the frequency stability significantly in the experiment with a 10-GHz signal and a 50-km fiber. The degradation could be improved by using 1550-nm zero-dispersion-shifted fiber (DSF) instead of the SMF. Effects of the PMD and polarization scrambling were experimentally shown with the DGD generator. The required stability of the reference signal source for precise fiber system evaluation was also shown.

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